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Experimental Study on System Stability Evaluation in Parallel Running of a Superconducting Generator and a SMES

Y. Shirai, T. Nitta, and M. Yamada

***Abstract*—Parallel running operation of 100 kVA Superconducting Generator (SCG) with high response excitation and 0.4 MJ SMES (Superconducting Magnet Energy Storage) was carried out. The exciter capacity of the high response excitation is rather large compared with that of conventional generators. The exciter controller, that is, AVR (Automatic Voltage Regulator) and PSS (Power System Stabilizer) are designed taking the exciter power change at the excitation into account to improve the system stability. The SMES can also improve the power system stability. The SMES can give the small active power modulation of sinusoidal wave to the system. The system responses due to the SMES power modulation were observed and analyzed in order to evaluate the designed control functions of AVR, PSS and SMES. Frequency characteristics of the designed control functions were obtained from on-line data of the system. The system stability of parallel running of the SCG and the SMES was evaluated by use of SMES power control.**

***Index Terms*—Excitation control, power system stability, SMES, superconducting generator.**

I. Introduction

SUPERCONDUCTING Generators (SCGs) have many advantages such as small size, weight, high efficiency and so on. Many studies have been done on SCGs [1]–[3]. They can improve power system stability in steady states and also in transient states with high response excitation. An experimental 100 kVA SCG with high response excitation whose pet name is Hesper 1 was designed and made. Several experiments for power system stability using an artificial transmission line were carried out [4]–[6]. A 1.2 MJ Superconducting Magnet Energy Storage (SMES) unit of toroidal magnet type (three module magnets) was designed and made by KEPCO, Japan. Basic tests were carried out and it was confirmed that the SMES has good feature in power system stabilization control [7]. We proposed a new usage of SMES, that is, on-line diagnosis of power system operating conditions by use of SMES [8]. The SMES, which is installed for power system stabilization, for example, can give a small continuous power disturbance of known pattern (such as a sinusoidal wave) with very small influence on power system. By monitoring the small power oscillation of line powers or generator output powers due to the SMES power change, a dynamic stability characteristic of the system is evaluated [8].

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TABLE I
RATINGS AND MACHINE CONSTANTS OF HESPER 1

specifications		
rated capacity	100(kVA)	
rated voltage	220(V)	
rated current	263(A)	
rated field voltage	2(V)	
rated field current	140(A)	
rated power factor	0.9(lag.)	
rated speed	1800(rpm)	
pole	4(poles)	
phase	3	
ceiling voltage	120(V)	
machine constants		
synchronous reactance	Xd	0.34(p.u.)
d-axis transient reactance	Xd'	0.32(p.u.)
d-axis subtransient reactance	Xd"	0.20(p.u.)
negative-phase-sequence reactance	X2	0.20(p.u.)
open-circuit time constant	Tdo'	80(sec)
open-circuit subtransient time constant	Tdo"	0.02(sec)
field inductance	Lf	1.14(H)

TABLE II
SPECIFICATION OF SUPERCONDUCTING MAGNET OF SMES

ratings	
rated capacity	422 kJ
rated voltage	400 V
rated current	350 A
inductance	6.89 H
material of superconductor	NbTi

In this paper, 100 kVA SCG with high response excitation and infinite bus system including 0.4 MJ SMES (one of three toroidal modules is used) is considered. The system stability of parallel running of the SCG and the SMES is evaluated by use of SMES power control unit. The field coil of SCG with high response excitation is one of a pulse coil of a certain stored energy. Therefore the exciter controller, that is, AVR (Automatic Voltage Regulator) and PSS (Power System Stabilizer) should be designed taking the exciter power change at the excitation into account in order to improve the system stability. The SMES

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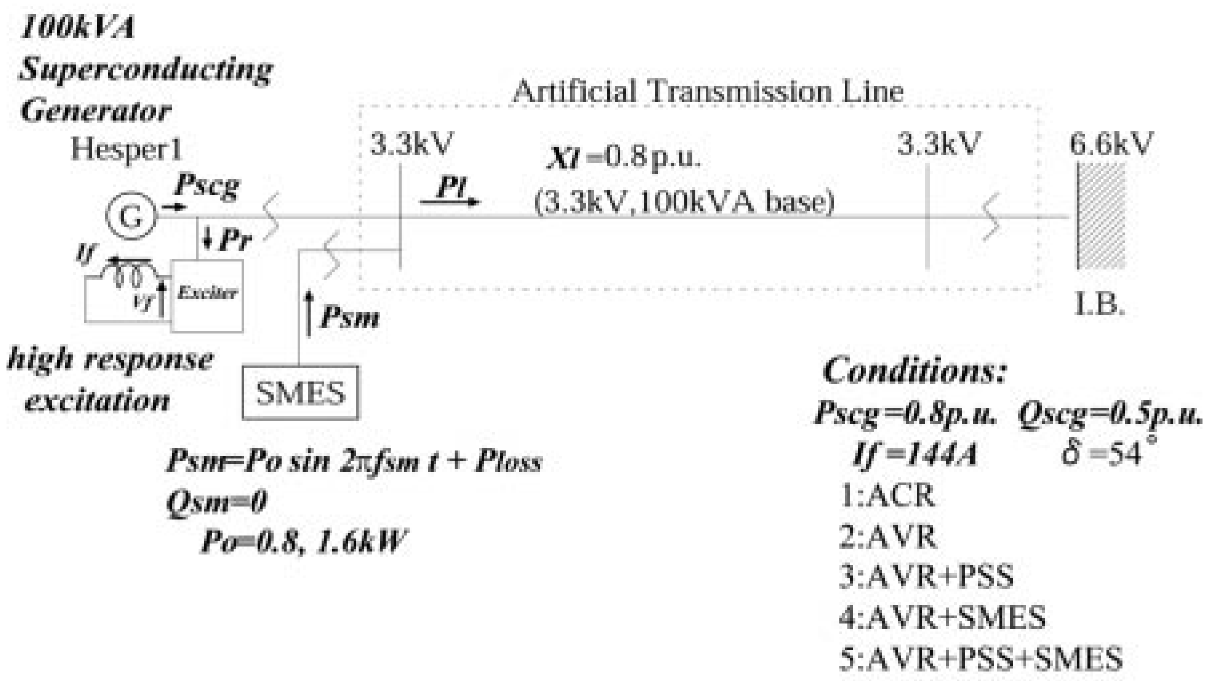

Fig. 2. Experimental system and conditions.

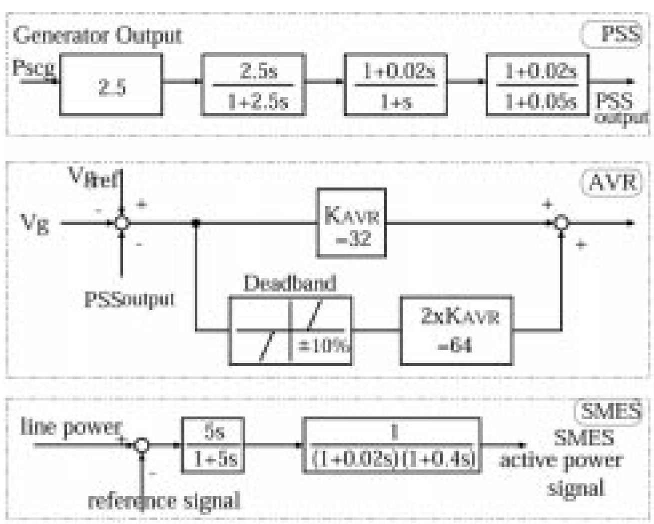

Fig. 1. Block diagram of exciter control (AVR and PSS) and power system stabilization control of SMES.

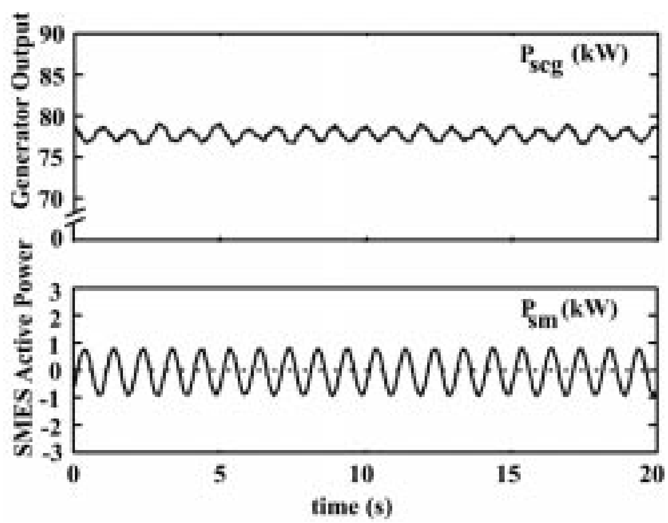

Fig. 3. SMES power disturbance ($P_0 = 0.8$ kW, $f_{sm} = 1$ Hz) and the generator power.

can also improve the power system stability. The designed control function of AVR, PSS and SMES are evaluated by use of SMES power control.

II. Experimental System

A. SCG With High Response Excitation Control and SMES

1) Experimental SCG (Hesper 1): The 100 kVA SCG (Hesper 1) was designed and manufactured so that the high response excitation is possible. The specification of Hesper 1 is shown in Table I. The rated capacity and the rated voltage of Hesper 1, that is, 100 kVA and 220 V, respectively, are the base values of per unit. The ceiling voltage is determined to be 120 V (60 p.u.) so that the magnetic flux linkage of air gap would be identical to that of large capacity SCGs designed by some feasibility studies. The superconducting field magnet is made of NbTi wire and designed for high response excitation.

2) SMES System: 1.4 MJ toroidal type SMES unit consists of three modules. One of the three modules was used for the experiment. Specification of the superconducting magnet of SMES is shown in Table II. Inverter and chopper system is applied to AC/DC/converter. The rated capacity, AC rated voltage, DC rated voltage of inverter are 20 kVA, 200 V and 400 V, respectively. The rated voltage and current of the chopper are 400 V and 350 A.

3) Exciter for SCG With High Response Excitation: The time constant T'_{do} of SCG is very large compared with that of the conventional generator [6]. Therefore, the capacity of the

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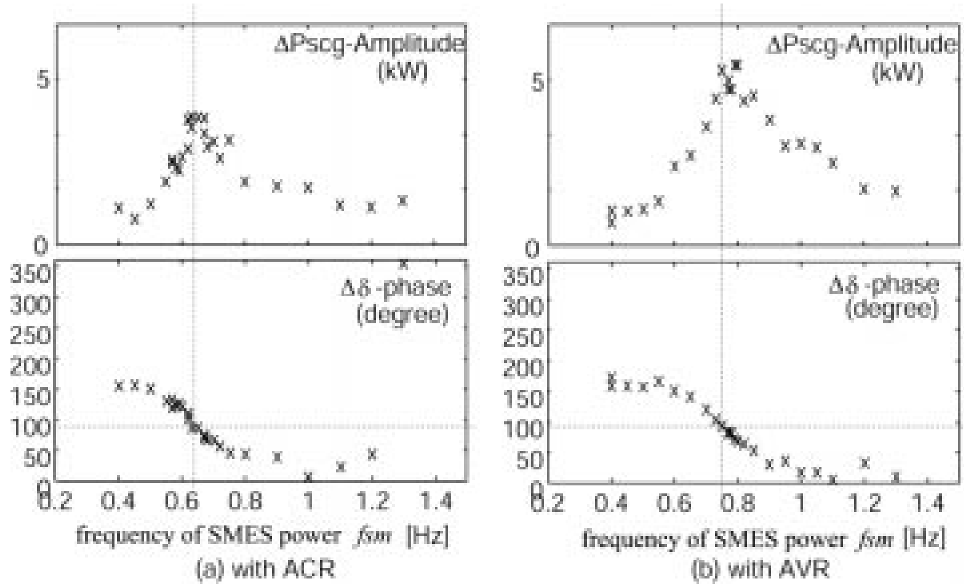

Fig. 4. Frequency characteristics of the generator power swing with [ACR] and [AVR] controls.

exciter for SCGs with high response excitation becomes larger than that for the conventional machine. The exciter power at quick change of the field current is large enough to affect the power system stability in a self-excited operation in which the exciter is connected to the generator terminal. The exciter power should be taken into account in the design of the exciter control (AVR and PSS). The thyristorized exciter is used. It is controlled by a digital automatic voltage regulator (AVR) system, whose block diagram is shown in Fig. 1.

The AVR gain of SCG with high response excitation must be larger than that of conventional generator because of the large time constant T'_{do}. In the steady state operations, however, the large AVR gain reduces the power system stability margin. Therefore, PSS (Power System Stabilizer) is necessary and AVR function has dead-band to switch the gain from $K_{AVR} = 32$ for small disturbances to $2 \times K_{AVR}$ for large disturbances [5].

B. Experimental System

The experimental power system is shown in Fig. 2. The system is considered to be a one-machine infinite bus system. Output power of 100 kVA SCG flows through the transmission line to 6.6 kV power source (assumed as the infinite bus). The 0.4 MJ SMES is installed at the generator terminal.

The transmission line reactance is 0.8 p.u. (3.3 kV, 100 kVA base). The output power of SCG is 0.8 p.u. (80 kW). The field current is 144 A. The operating cases of the exciter and the SMES are set as follows:

1) [ACR (Constant field current control)]
2) [AVR (Automatic Voltage Regulation Control)]
3) [AVR + PSS (Power System Stabilization control)]
4) [AVR with SMES stabilizing control]
5) [AVR + PSS with SMES stabilizing control].

With these operating cases, the frequency characteristics of these stabilizing control systems are evaluated on-line by use of SMES power modulation. The small power disturbance is given to the system from SMES. The active power P_{sm} of SMES is changed according to the sinusoidal signal

$$P_{sm} = P_0 \sin(2\pi f_{sm} t) + P_{loss}, \tag{1}$$

where P_0 is the amplitude of the power change (0.8 and 1.6 kW), f_{sm} is the frequency of the power change (from 0.4 to 1.3 Hz) and P_{loss} is the loss of SMES, while the reactive power Q_{sm} of SMES is 0 kVar. The power system responses of the small continuous disturbances are observed as shown in Fig. 3, for example. The generator output P_{scg} contains small oscillation of amplitude =1 kW around 78 kW due to the SMES power modulation of 0.8 kW amplitude.

The amplitude and the phase of the deviation ΔP_{scg} of generator power, the deviation $\Delta\delta$ of the rotor angle, the deviation ΔP_r of the exciter power, the PSS control signal, the SMES stabilizing control signal P_{stab} are obtained by Fourier Transformation for various frequencies f_{sm} of the SMES power change.

III. Experimental Results

A. Difference Between ACR and AVR Control

The frequency characteristics of the power oscillation due to the small SMES power disturbance with [ACR] and [AVR] control are shown in Fig. 4(a) and (b), respectively. The amplitude of ΔP_{scg} has peak value (4 kW) at the frequency of 0.62 Hz with ACR control when the phase of the deviation $\Delta\delta$ of the rotor angle (base phase: P_{sm}) is 90 degrees.

The frequency of 0.62 Hz is considered to be the natural frequency of the system. The natural frequency of the system with AVR-control is 0.75 Hz and the peak value of ΔP_{scg} is 5.5 kW. As the natural frequency is higher, the synchronizing force of the generator becomes larger. It can be said that the AVR-control increases the synchronous force, but reduces the damping force.

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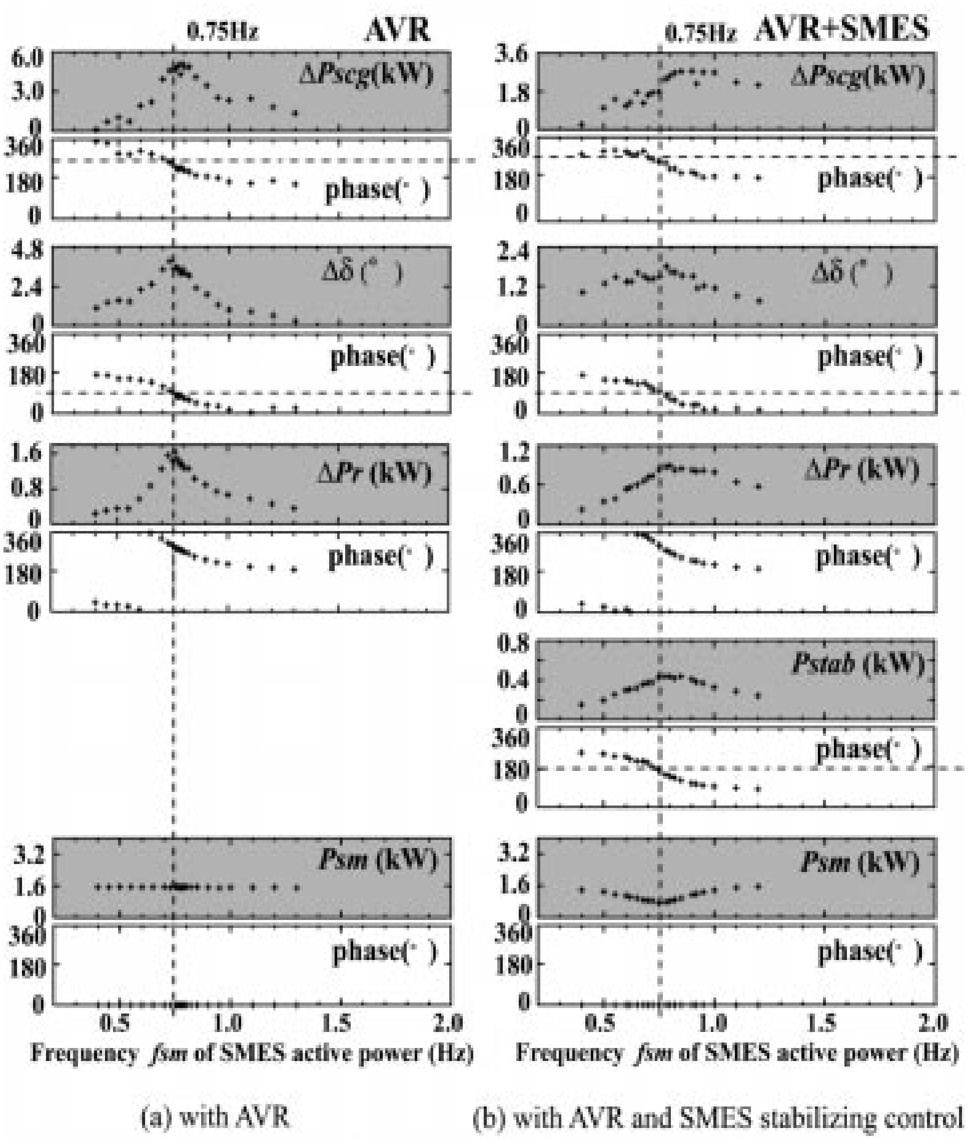

Fig. 5. Frequency characteristics (amplitude and phase) of power swing with AVR and AVR + SMES stabilizing control.

B. Power Stabilization Control of SMES

The frequency characteristics of the power oscillation due to the small SMES power disturbance with [AVR] and with [AVR+ SMES power stabilizing control] are shown in Fig. 5(a) and (b), respectively. The amplitude and phase of ΔP_{scg}, $\Delta\delta$, ΔP_r, P_{sm} and P_{stab} signal are shown for the frequency f_{sm} of SMES active power. The natural frequency 0.75 Hz does not change by [SMES power stabilizing control], however, the amplitude of ΔP_{scg}, $\Delta\delta$ decreases almost a half of those with only [AVR]-control. It is pointed out that the [SMES power-stabilizing control] can improve the damping of the system without reducing synchronizing force.

The phase difference between the deviation ΔP_r of the exciter power and P_{sm} at the natural frequency is about −90 degrees. This means that the exciter power due to the [AVR]-control accelerates the power oscillation and reduces the damping force of the system.

C. PSS Control

The frequency characteristics of the power oscillation due to the small SMES power disturbance with [AVR + PSS] are shown in Fig. 6(a). The amplitude and phase of ΔP_{scg}, $\Delta\delta$, ΔP_r, P_{sm}, *PSS signal* are shown for the frequency f_{sm} of SMES active power. The amplitude of ΔP_{scg} becomes one-third of that with [AVR]-control. The [PSS]-control increases the damping force of the system. Comparing the phase characteristics of ΔP_r in Fig. 6(a) with that of Fig. 5(a) and (b), the phase difference between ΔP_r and P_{sm} is shifted from −90 degrees to 10 degrees by the [PSS]-control. It can be pointed out that the [PSS]-control compensates the negative damping of the [AVR]-control, and then, the exciter power P_r is effectively used to stabilize the power system oscillation. The natural frequency changes from 0.75 Hz to 0.71 Hz. The synchronizing force is reduced a little by the [PSS]-control.

The frequency characteristics of the power oscillation with [AVR + PSS + SMES-stabilizing-control]

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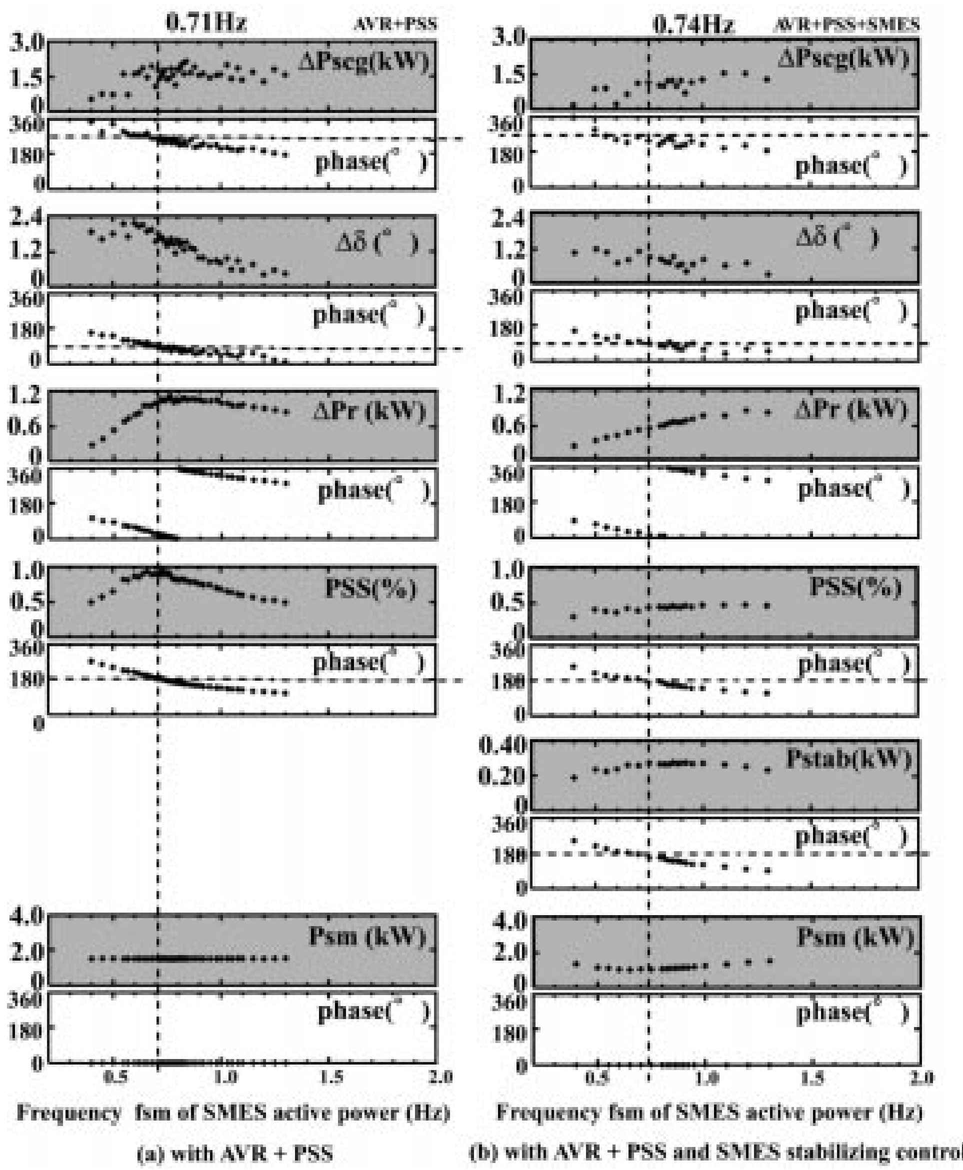

Fig. 6. Frequency characteristics (amplitude and phase) of power swing with [AVR + PSS] and [AVR + PSS + SMES] control.

are shown in Fig. 6(b). The amplitude and phase of ΔP_{scg}, $\Delta\delta$, ΔP_r, P_{sm}, P_{stab}, *PSS signal* are shown for the frequency f_{sm}. The power oscillation is damped without any bad interference among these control schemes.

IV. Conclusion

Parallel running operation of 100 kVA Superconducting Generator with high response excitation and 0.4 MJ SMES was carried out. The exciter controller (AVR and PSS) for high response excitation is designed taking the exciter power change at the excitation into account to improve the system stability. The SMES can also improve the power system stability.

The designed control functions of AVR, PSS and SMES were evaluated by use of SMES. The system response due to the SMES power modulation were observed and analyzed. Frequency characteristics of the designed control functions were obtained from on-line data of the system. The results obtained are as follows:

1) Natural frequency of the system including the control units is obtained from on-line data.
2) Synchronous and damping forces of the system are estimated experimentally.
3) [AVR]-control increases the synchronous force but reduces the damping force.
4) [SMES power stabilizing control] can improve the damping of the system without reducing the synchronizing force.
5) [PSS]-control is the most effective in increasing damping force and it reduces the synchronizing force a little. The experimental result shows that the [PSS]-control adjust the phase of exciter power so as to improve the system stability.

The system stability of parallel running of the SCG and the SMES is evaluated by use of SMES power control unit.

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